

Charge-dependent anisotropic flow studies and the search for the Chiral Magnetic Wave in ALICE

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Abstract

Theoretical calculations have shown the possibility of P-violating bubbles in the QCD vacuum, which in combination with the strong magnetic field created in off-central heavy-ion collisions lead to novel effects such as the Chiral Magnetic Effect (CME) and the Chiral Separation Effect (CSE). A coupling between the CME and the CSE produces a wave-like excitation called the Chiral Magnetic Wave (CMW). The CMW produces a quadrupole moment that always has the same sign and is therefore present in an average over events. In this talk we present a series of charge-dependent anisotropic flow measurements in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV in ALICE, using two- and three-particle correlators with unidentified hadrons. The relation of these measurements to the search for the CMW is discussed.

Keywords: Flow, Parity, Local Charge Conservation, Chiral Magnetic Wave

1. Introduction

Off-central heavy-ion collisions create an almond-shaped overlap region, which extends above and below the reaction plane. The pressure gradients in-plane are greater than those out-of-plane, which creates an azimuthal anisotropy in momentum space as the system expands. Additionally, the spectator protons can be thought of as small but very dense currents. Since there are two currents close-by pointing in opposite directions, the induced magnetic field from each current adds linearly in the region between them, creating a very large and relatively homogeneous magnetic field in the same location in configuration space as the medium created in the overlap region. The interaction of the magnetic field with the produced particles in a region of space with topologically non-trivial gluon field configurations leads to novel effects like the Chiral Magnetic Effect (CME) [1] and the Chiral Separation Effect (CSE) [2].

The CME and CSE can be summarized succinctly in a pair of equations [3],

$$\vec{J}_V = \frac{N_c e}{2\pi^2} \mu_A \vec{B}, \quad (1)$$

$$\vec{J}_A = \frac{N_c e}{2\pi^2} \mu_V \vec{B}. \quad (2)$$

Equation 1 is for the CME, and indicates that a vector current J_V (for example an electric current) is coupled to an axial chemical potential μ_A , oriented along the the magnetic field B . Equation 2 is for the CSE, and indicates that an axial current J_A is coupled to a vector chemical potential μ_V (for example the scalar electric potential), again oriented along the the magnetic field.

¹ A list of members of the ALICE Collaboration and acknowledgements can be found at the end of this issue.

One can tell by inspection that the two currents are coupled. By changing to the chiral basis, $V = R + L$ and $A = R - L$, one can derive two equations indicating two electric currents that always point in opposite directions, leading to an electric quadrupole moment that always has the same sign. A detailed explanation and derivation is given in [3]. This effect is shown schematically in Figure 1.

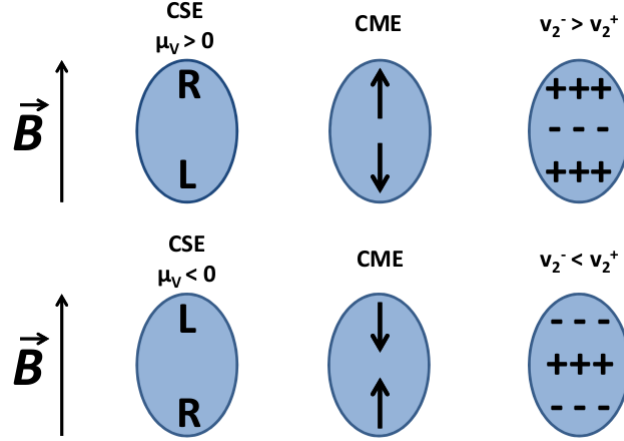


Figure 1. Cartoon showing the basic picture of the Chiral Magnetic Wave for the two cases $\mu_V > 0$ and $\mu_V < 0$.

In Figure 1, the upper row shows an example where the plasma has a positive electric charge state, i.e. $\mu_V > 0$. This causes a CSE current pointing upwards, leading to an excess of right-handed particles above the reaction plane and an excess of left handed particles below it. This means that above the reaction plane one has $\mu_A > 0$ and below it one has $\mu_A < 0$. This then leads to two oppositely directed CME currents, each pointed away from the reaction plane. This leads to a positive electric quadrupole, with excess positive charges out of plane at the poles and excess negative charges in plane at the equatorial region. Finally, under the hydrodynamic expansion of the medium, the equatorial region has a larger flow velocity due to the larger pressure gradients in plane, and therefore one observes large v_2 for negative particles than positive particles, i.e. $v_2^- > v_2^+$. The lower row of the figure shows the same schematic for the opposite case with $\mu_V < 0$, which leads to exactly the same effect with all signs flipped. A detailed explanation and derivation of how the presence of CMW affects the final state observables in this way is given in [4]

2. Methodology and observables

From the previous section, the most intuitive observable would be v_2 (or v_n to explore possible higher harmonic effects) as a function of the event charge asymmetry A , which is defined as $A = \frac{N^+ - N^-}{N^+ + N^-}$, where N^+ and N^- represent the number of positive and negative particles, respectively, measured in some well-defined region of phase space, i.e. for some p_T selection and, more importantly, some η acceptance. Indeed, this observable has been proposed theoretically [4] and measured experimentally in Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV by the STAR collaboration [5]. However, one of the issues with this observable is that the slope of v_n vs A is not independent of experimental effects (for example tracking efficiency) and therefore requires a correction factor.

In this analysis, we use a novel three particle correlator [6] that is independent of efficiency and therefore requires no correction. The three particle correlator is $\langle \cos(n(\phi_1 - \phi_2))q_3 \rangle$, where ϕ_1 and ϕ_2 are the azimuthal angles of particles 1 and 2, and q_3 is the charge (± 1) of particle 3. The $\cos(n(\phi_1 - \phi_2))$ part is estimated using the cumulant method and denoted as $c_n\{2\}$. In the absence of charge dependent correlations, the correlator should factorize, i.e.

$$\langle \cos(n(\phi_1 - \phi_2))q_3 \rangle - \langle q_3 \rangle \langle \cos(n(\phi_1 - \phi_2)) \rangle = 0. \quad (3)$$

Note that when the charge of the third particle is averaged over all particles in the event (in the specified kinematic acceptance), the mean is equal to the charge asymmetry, i.e. $\langle q_3 \rangle = \langle A \rangle$.

3. Results

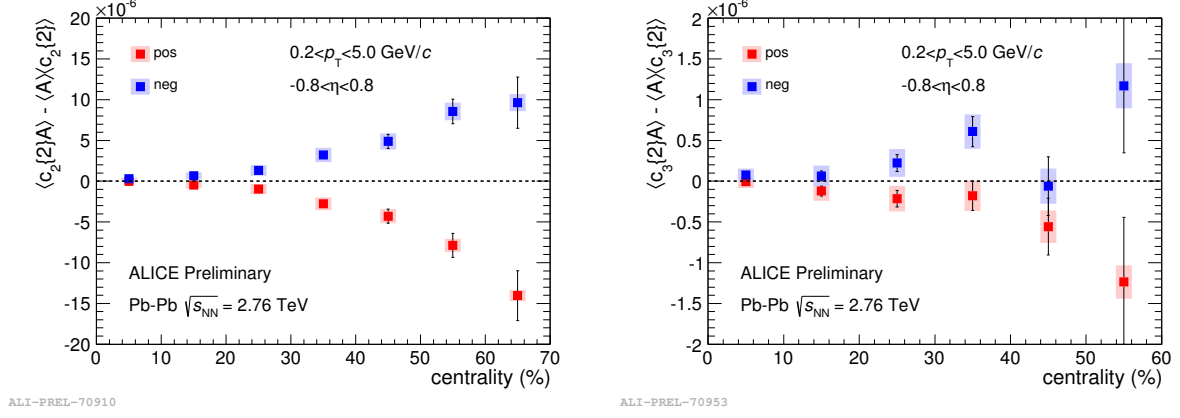


Figure 2. Three particle correlator for the second (left panel) and third (right panel) harmonic as a function of centrality.

Figure 2 shows the three-particle correlator for the second (left panel) and third (right panel) harmonic as a function of centrality. For the second harmonic one sees a substantial increase in the correlation strength as the collisions become more peripheral. This could be caused by any possible combination of several factors. The magnetic field strength increases as the impact parameter increases and thus the current gets stronger. This would cause the correlations due to the CMW to get stronger. Additionally, effects due to local charge conservation (LCC, i.e. the creation of balanced charge pairs close by in position space) could play a role [7]. Since central collisions have more combinatoric (uncorrelated) pairs, the correlations due to LCC suffer combinatorial dilution. Note that neither of these necessarily comes at the expense of the other. Non-flow 3-particle correlations may also contribute, for example from jet-like correlations and 3-body decays. However, a comparison to HIJING Monte Carlo was performed and the three-particle correlator was found to be statistically insignificant, indicating these effect play at most a very small role. For the third harmonic one sees a small but non-zero correlation. The physical origin is not clear, though background from LCC is likely a contributor. Additional factors could also contribute, such as interference between the second and third harmonics, higher order multipole moments of the P-violating effects, and other possible effects.

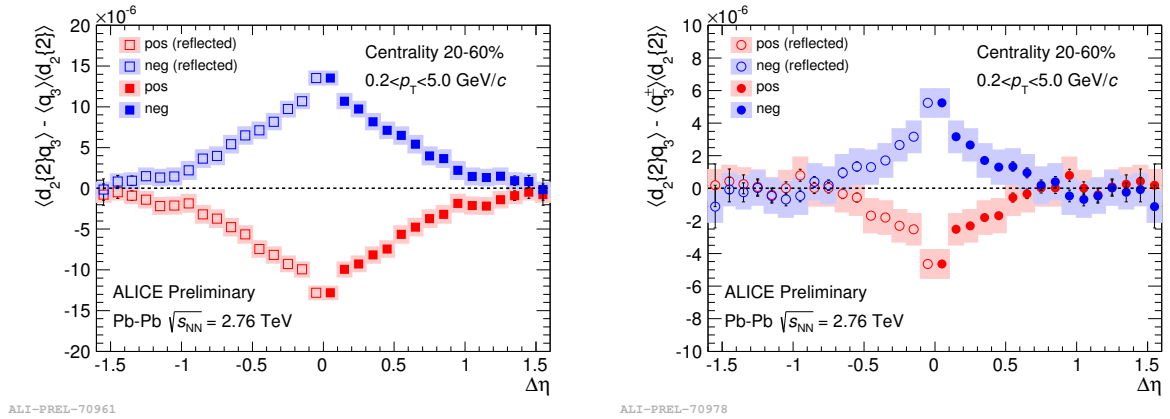


Figure 3. Three particle correlator for the second harmonic. The left panel shows the results with charge independent subtraction and the right panel shows the results with charge dependent subtraction.

Figure 3 shows the three-particle correlator for the second harmonic as a function of $\Delta\eta = \eta_1 - \eta_3$. The left panel shows the result where $\langle q_3 \rangle$ is subtracted, meaning the same average charge is subtracted for each charge. This correlator is likely proportional to $\frac{v_n^2 B(\Delta\eta)}{dN/d\eta}$, where $B(\Delta\eta)$ is the charge balance function. See [7] for a treatment of LCC and the charge balance function as related to searches for local P-violating effects and [6] for a discussion of those effects on this particular observable. Contrariwise, the right panel shows the charge-dependent subtraction of $\langle q_3^\pm \rangle$, meaning the correlation between the the charge of particle 1 (q_1) and q_3 is taken into account. One sees a substantial reduction in the effect in terms of both strength and in range, i.e. the length of the correlation in $\Delta\eta$. From this we may conclude that this subtraction removes some amount of the LCC contribution, though a detailed theoretical treatment is needed.

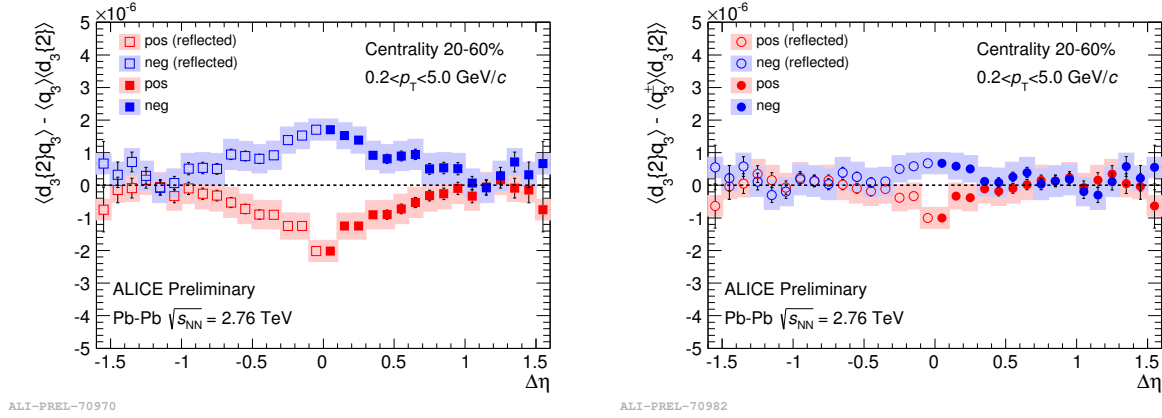


Figure 4. Three particle correlator for the third harmonic. The left panel shows the results with charge independent subtraction and the right panel shows the results with charge dependent subtraction.

Figure 4 shows the three-particle correlator for the third harmonic as a function of $\Delta\eta$. As for the previous figure, the left panel shows the charge independent subtraction and the right shows the charge dependent subtraction. Note that the correlation strength for the unsubtracted is rather strong, whereas the charge dependent subtraction removes the correlation almost entirely.

4. Conclusions

A novel three-particle correlator is employed to search for the CMW. The results for the second and third harmonic were shown as a function of centrality and $\Delta\eta$. Although LCC is thought to be a major background to these measurements, the charge dependent subtraction can reduce this effect. Even after the reduction some charge dependent signal is still observed, which may indicate that some LCC effect remains, or which may be due to P-violating effects like the CMW, or some combination of factors. Further input from theory is needed to give detailed constraints on the magnitude and range of LCC vs CMW correlations.

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